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Hadron Spectroscopy at RHIC

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ABSTRACT

A description is given of the physics opportunities at RHIC regarding quark-gluon spectroscopy. The basic idea is to isolate with appropriate triggers the subprocesses pomeron + pomeron → hadrons and $\gamma^* + \gamma^* \to$ hadrons with the net effective mass of hadrons in the range of 1.0 to 3.0 GeV, in order to study the hadronic states composed of u, d, and s and gluons. The double-pomeron interactions are expected to produce glueballs and hybrids preferentially, while the two-offshell-photon initial states should couple predominantly to quarkonia and multiquark states. A plethora of J^{PC}-exotic mesons can be produced either directly in both types of interactions or in association with a single recoil photon in the final state.

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1. Introduction

In this note is described a conceptual design for carrying out a study of quark-gluon spectroscopy at RHIC.

The idea is derived from a douple-pomeron exchange trigger which was successfully implemented in R807 (an ISR experiment at CERN)[1]. The resulting $\pi^+\pi^-$ (see Fig.1) and K^+K^- spectra provided key ingredients in the identification of three $J^{PC} = 0^{++}$ states with masses near 1.0 GeV, one of which may be the scalar glueball[2].

For the trigger to succeed, it is necessary that for $p \times p$ the recoiling beam particles come off at a very small angle, $\theta \leq 2mr$. At RHIC energies this corresponds to installing a set of four 'Roman pots,' two on each side up and down, 10m away from the intersection region. Precision 5x5cm mini-drift chambers and scintillation counters will be installed in each Roman pot to detect and trigger on the scattered beam particles. The intersection region will be instrumented with a 4π-detector consisting of cylindrical drift chambers, ring-imaging Cerenkov counter and lead-scintillator barrel counters, all within a 5.4m-long solenoid magnet with a 3.6m coil diameter, patterned after the Mark III[3] and the ARGUS apparatus.

It was shown in R807 that imposition of momentum balance in the direction perpendicular to that of the beam particles results in pure exclusive events, as follows:

$$pp \rightarrow\ p\left(\pi^+\pi^-\right)p$$
$$pp \rightarrow\ p\left(K^+K^-\right)p$$

where the systems shown in the parentheses indicate the particles detected in the central detector. In the proposed RHIC experiment, the central detector will be optimized for charged as well as neutral particles with momenta up to 3 GeV/c, so that the following reactions can be studied:

$$pp \to p(\eta\eta)p$$
$$pp \to p(\omega\omega)p$$
$$pp \to p(\phi\phi)p$$
$$pp \to p(\eta\pi\pi)p$$
$$pp \to p(\omega\pi\pi)p$$
$$pp \to p(K\bar{K}\pi)p$$
$$pp \to p(p\bar{p}\pi)p$$

where the parentheses indicate again the central system.

The momentum transfer squared from initial to final protons is given by

$$-t \simeq (p\alpha)^2 \simeq q^2 \simeq 0.025\ (\mathrm{GeV/c})^2$$

where $p = 250$ GeV/c is the momentum of the initial proton and $\alpha \simeq 2mr$ is the scattering angle of the proton in laboratory and $q \simeq 0.5$ GeV/c is the momentum of the final proton perpendicular to the beam. Since the slope of $-t$ distributions is expected to be around 10 GeV^{-2} at the top end of RHIC energy[4], the value $-t$ is sufficiently small to guarantee a pomeron exchange, and a double pomeron exchange reaction will result if both the final protons come off with $-t \leq 0.025$ (GeV/c)^2. In this case the central rapidity region corresponds in effect to the reaction

$$\mathbf{PP} \to \text{hadrons}$$

where $\mathbf{P}$ stands for a pomeron and the $\sqrt{s}$ for this subprocess ranges from 1.0 to 3.0 GeV. The upper limit on the $\sqrt{s}$ is not an inherent limitation; for a study of the states with the c quark, it should be extended to 5.0 GeV.

Let M denote the invariant mass of the total hadronic system, i.e. the $\sqrt{s}$ for the process given above. Then,

$$M^2 \simeq \epsilon_1\epsilon_2\,(2p)^2 + t_1 + t_2 - 2\mathbf{q_1}\cdot\mathbf{q_2}$$

where subscripts 1 and 2 denote final deflected beam particles and $1-\epsilon$ stands for the Feynman x variables[5]. Replacing $-t$ by q^2, one obtains

$$M^2 \simeq \epsilon_1\epsilon_2\,(2p)^2 - (\mathbf{q_1}+\mathbf{q_2})^2$$

From this one sees that

$$\epsilon_1 \sim \epsilon_2 \sim \frac{M}{2p} \simeq 4 \times 10^{-3}$$

for $M = 2$ GeV and $p = 250$ GeV/c.

According to S. Y. Lee (BNL), one can choose an insertion mode in which the angular dispersion of the beam can be held to as low as 1.0mr at 10m from the intersection. At this point, the deflected particles may range from 10mm to 40mm measured from the beam center. This corresponds to q in the range of 0.25 GeV/c to 1.0 GeV/c for a proton beam at 250 GeV/c. Within the Roman pots there will be a set of four drift-chamber modules and two scintillation counters, each with an active area measuring 50x50mm.

The same experimental setup can be applied to heavy-ion collisions, e.g. those involving gold. M. Rhodes-Brown (BNL) points out that in the extreme low-momentum-transfer region the photon-photon interactions become competitive with the double-pomeron production,

$$\sigma \sim (Z\alpha)^4 \sim 0.1$$

for $Au \times Au$ at 100 GeV/u. The heavy ions of RHIC thus provide an opportunity for a study of two offshell-photon interactions,

$$\gamma^*\gamma^* \rightarrow \text{hadrons}$$

where $\sqrt{s}$ for this subprocess is in the range 1.0–3.0 GeV. Note that the photons involved are highly offshell indeed; the $-t$ corresponding to the photon is given by

$$-t \simeq \; q^2 \simeq \; (p \times \; 1mr)^2 \simeq \; 20 \; (\text{GeV/c})^2$$

where $p = 197 \times 100$ GeV/c and 1mr is the allowed angular dispersion of the beam.

The coherent production of hadrons by the two-photon process involves extremely sharp $-t$ distributions. According to A. Skuja and D. H. White[6], the slope of the $-t$ distributions is 700 GeV^{-2} for $Au \times Au$ at 100 GeV/u, indicating that the beams simply pass through undeflected in the region where the cross section is appreciable. The energy loss is also extremely small,

$$\epsilon_1 \sim \epsilon_2 \sim \frac{M}{2p} \simeq 5 \times 10^{-5}$$

for $M = 2$ GeV and $p = 197 \times 100$ GeV/c. It is seen that this loss factor is well within the allowed beam dispersion of RHIC.

It therefore follows that a proper $\gamma^*\gamma^*$ trigger calls for something other than the Roman pots, i.e. it has to rely on a veto on the deflected beam, by a set of four lead-scintillation sandwich barrel counters located at 10m and 40m away from the intersection point. A barrel counter consists of six truncated wedge detectors with widths 5cm and 20cm and 50cm long. Its design is identical to that of the EM calorimeter in the central detector, as described in the next section. Note that each barrel counter covers radial distances down to 5cm radius from the beam line. With this setup, one can span the deflection angles from 1.25mr to 5mr.

It is necessary, in addition, to veto on the diffractive dissociation of the beam. For the purpose, the end iron-plates of the magnet will be cut out at 100cm radius, and a hadron calorimeter will be installed, which consists of 30 iron-scintillation sandwiches, designed to veto hadrons above 10 GeV/c. Additional material on the calorimeter is given in the next section.

The quark-gluon spectroscopy is a study of hadrons with mass in the range between 1.0 and 3.0 GeV, if the constituent quarks are comprised only of u, d and s. The initial state of the double-pomeron production is in reality a flavorless and colorless gluonic bundle. It follows therefore that the final state should be rich in gluonic excitations, i.e. glueballs and hybrids. In contrast, two offshell photons couple preferentially to charged quarks, e.g. $u\bar{u}$ or $c\bar{c}$ if the energy is high enough, leading to the production of quarkonia and multiquark states.

What quantum numbers are allowed for the initial state? Assuming a pomeron to be a $J^{PC} = 0^{++}$ state, one can expect for the double-pomeron initial state $I^G = 0^+$ and $J^{PC} = 0^{++}, 2^{++}, 4^{++}, etc.$ For the two-offshell-photon initial state, one may expect $I^G = 0^+, 1^-$ and $J^{PC} = (0,1,2,3,4,..)^{++}, (0,1,2,3,4,..)^{-+}$. It should be noted that $J^{PC} = (1,3,5,..)^{-+}$ is exotic and cannot couple to quarkonia. Observation of such a state would imply an exotic multiquark state. Study of J/ψ radiative decays proved to be a prolific source of information for hadronic states. One can perform a similar study at RHIC by examining the hadronic system recoiling off a single photon.

2. Central Detector

The central detector consists of a neutral and charged particle detection device with a 4π coverage, all housed in a moderate-size solenoid magnet with an inner radius of 155cm and 540cm long outside. The magnet uses Al coils inside the yoke producing a field strength of 0.5T. It is designed to identify up to a dozen particles with momenta in the range 0.05–2.50 GeV/c, for a study of meson systems with mass 1.0–3.0 GeV. The central detector is thus given the name QGS, for Quark-Gluon Spectrometer (see Fig.2).

The QGS consists of a drift-chamber module surrounding the beam pipe, followed by a ring-imaging Cerenkov counter (RICH), a time-of-flight (TOF) hodoscope and a lead-scintillation sandwich EM calorimeter, all within the magnet coil. Each end of the magnet is instrumented with a hadron calorimeter. These items are described briefly below.

The drift-chamber module is 3.2m long along the beam; it starts at a radius of 5cm and extends to 75cm. The size of drift cells is dictated by the time interval of 225ns between bunch crossings. The whole module is divided into 9 layers, each containing two axial sense wires and two stereo wires at angles from $40mr$ to $80mr$. In all there will be some 9100 sense wires. The rms error on the transverse momentum is estimated to be

$$\frac{\delta p_\perp}{p_\perp} = 1.5\%\ p_\perp(\text{ GeV/c})$$

assuming a measurement accuracy of $200\mu m$ and a field of 0.5T. The angular resolution is, from multiple scattering,

$$\delta\theta = \frac{1.3mr}{p_\perp(\text{ GeV/c})}$$

The particle identification is provided by the dE/dx measurement. Assuming an average of 36 measurements per track, the resolution is expected to be 15% FWHM. This provides a 3σ π/K separation up to about 0.6 GeV/c.

The RICH detector envisaged here is patterned closely after the conceptual design worked out by B. Ratcliff[7]. It extends from a radius of 75cm to 100cm and is 370cm long on the outside. The front segment consists of a 1cm-thick liquid Freon (C_6F_{14}) with an index of refraction $n = 1.277$, so that a relativistic particle produces Cerenkov light of 17cm radius at the end of a 13cm drift region. It is then followed by a 4.4cm-thick photon-conversion region containing C_2H_6 and TMAE (Tetrakis Dimethyl Amino Ethylene). The readout is accomplished by a system of 2950 10x10cm electronic pads. The drift time is about $25\mu s$, which implies that this RICH counter is not a trigger device. The offline π/K separation is impressive, starting at 0.03 GeV/c and extending to 3 GeV/c.

The TOF system is located at a radius of 100cm and is 3.8m long. It consists of 128 5x5cm scintillation counters, each viewed by two photomultipliers. The resolution is conservatively estimated to be 250ps, providing a 3σ π/K separation from 0.08 GeV/c to 0.6 GeV/c. Thus it can be used as an independent check of both the drift-chamber module and the RICH counter. It can also be used as a component in the charged particle triggers.

The EM calorimeter covers radii from 105cm to 155cm and is 480cm long outside. It consists of 3200 10x10cm towers, each with 84 layers of 6mm lead-scintillation sandwiches (1mm of lead and 5mm of plastic scintillator) for a total of $15X_0$ and viewed by a photomultiplier through a wave-length shifter. A similar device was used by ARGUS[8]. The energy resolution is expected to be

$$\frac{\delta E}{E} = \frac{7\%}{\sqrt{E(\text{ GeV})}}$$

for the photon energy from 0.07 GeV to 3.0 GeV. This device can be used to detect $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$ and $\omega \to \pi^0\gamma$.

The end caps of the magnet have cutouts with radius 100cm, and two hadron calorimeters with the active areas at radii from 5cm to 100cm will be installed in this space. The calorimeter consists of 30 iron-scintillation sandwiches. Both the iron plate and the plastic scintillator are 1cm thick, and the periphery of the scintillator is edged with a wave-length shifter, which is read out by a photomultiplier. It is estimated that the energy resolution is

$$\frac{\delta E}{E} = \frac{60\%}{\sqrt{E(\text{ GeV})}}$$

so that a 10 GeV/c particle can be measured with an accuracy of about 20%. For the $Au \times Au$ run, the two hadron calorimeters will be used to veto on any particle with energy greater than 10 GeV/c. It is expected that about 90% of all the diffractive dissociation events can thus be eliminated at the trigger level.

3. Triggers

The trigger for **PP** interactions relies on a set of four scintillation counters within the Roman pots. For $p \times p$ runs, two triggers are possible with the Roman pots, 'up-up' and 'down-down.' This means that both of the counters above (below) the beam line at either side of the intersection region are triggered for 'up-up' ('down-down'). The triggers will be augmented with signals from the QGS, utilizing among others the hits in the EM calorimeter. Each hit above the minimum energy threshold, but below the maximum allowed energy, e.g. 10 GeV, is treated with equal weight; a fast microprocessor sums up independently the x, y and z projections of the location of the hit with respect to the midpoint of the intersection region. The trigger requires that the three sums are within a small preset range. This algorithm ensures that an event with a large missing energy in any direction will be eliminated, on the average. Note also that this technique treats charged and neutral particles on an equal footing.

For $Au \times Au$ runs, instead of the Roman pots, the trigger relies primarily on signals from the QGS to pick out two-photon events, accompanied by vetos at two end-cap hadron calorimeters and the four lead-scintillation barrel counters located 10m and 40m away from the intersection region. The vetoes guard against the small-angle beam deflections and the diffractive dissociation of the beams.

A Monte Carlo study is planned to assess the efficacy of the x-, y- and z-projection methods described above in selecting production of low-mass hadrons in the central region.

4. Conclusions

In this note a brief description is given of an exciting opportunity to carry out a hadron spectroscopy experiment at RHIC. The key idea here is that by concentrating on the extreme double-peripheral region at RHIC, the machine is used to produce hadronic systems at low $\sqrt{s}$ in the range 1.0–3.0 GeV.

The subprocesses responsible for the hadronic system in the central region may be expressed either as pomeron + pomeron $\rightarrow$ hadrons or as $\gamma^* + \gamma^* \rightarrow$ hadrons. The double-pomeron interactions are expected to produce glueballs and hybrids preferentially, while the two-offshell-photon initial states should couple predominantly to quarkonia and multiquark states. A whole gamut of J^{PC}-exotic mesons $(0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, ..)$ may be seen either directly in both types of interactions or in association with a single recoil photon in the final state. Another important distinction is that the hadronic system from a double-pomeron interaction has zero net flavor, whereas an $I^G = 1^-$ meson can couple readily to a two-photon initial state.

The salient feature of this proposal lies in the fact that, for the first time, a study of the pomeron-pomeron interactions can be mounted with the same experimental setup as that of the photon-photon interactions.

The authors acknowledge with pleasure the opportunity for learning about the RHIC machine and the experiments being proposed at the 1990 BNL RHIC Workshop. They had useful conversations with S. Y. Lee and M. Rhodes-Brown of BNL during the Workshop.

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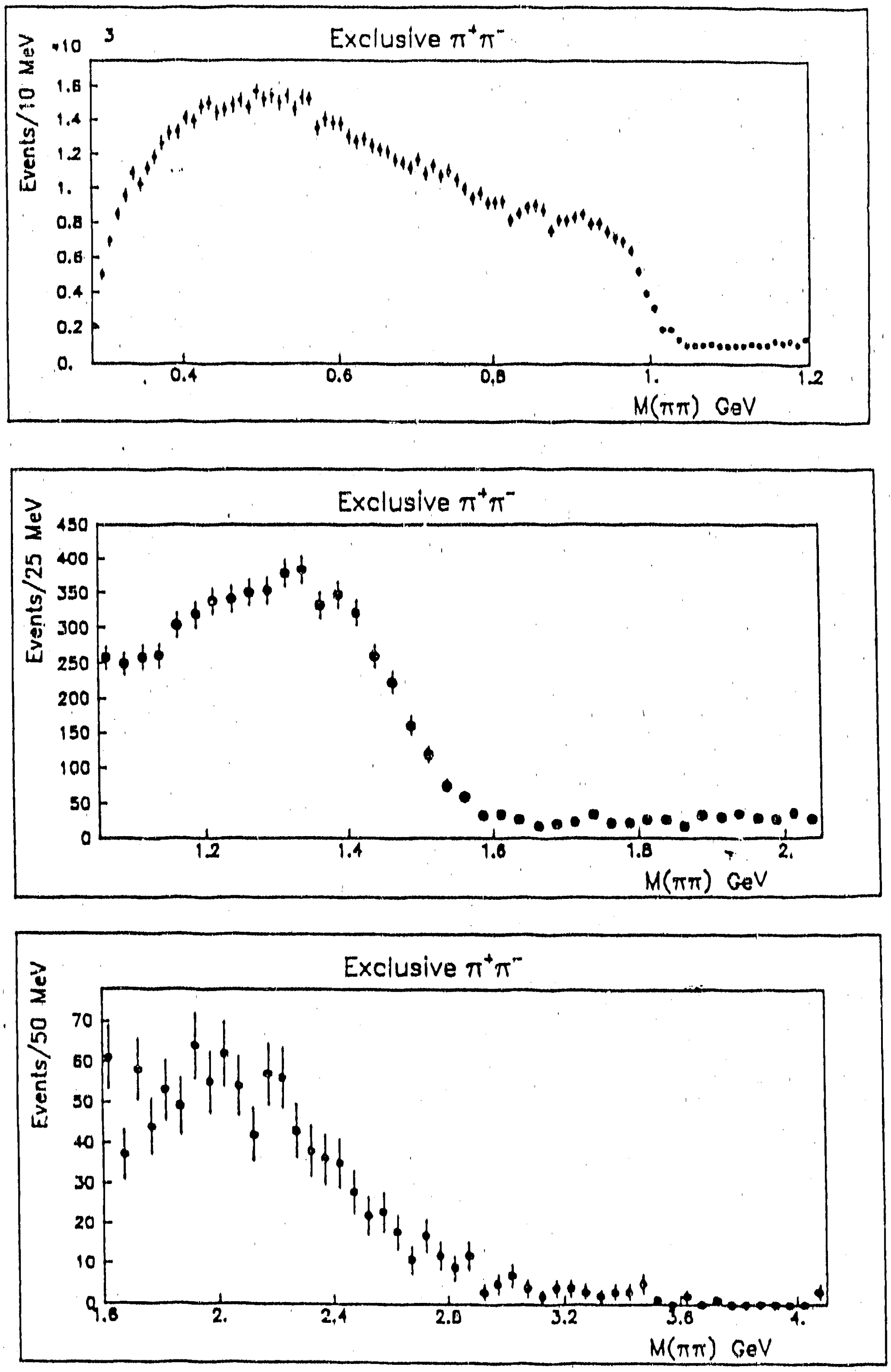

Figure 1: $\pi^+\pi^-$ spectra for $pp \to p(\pi^+\pi^-)p$ at $\sqrt{s}$ =63 GeV.

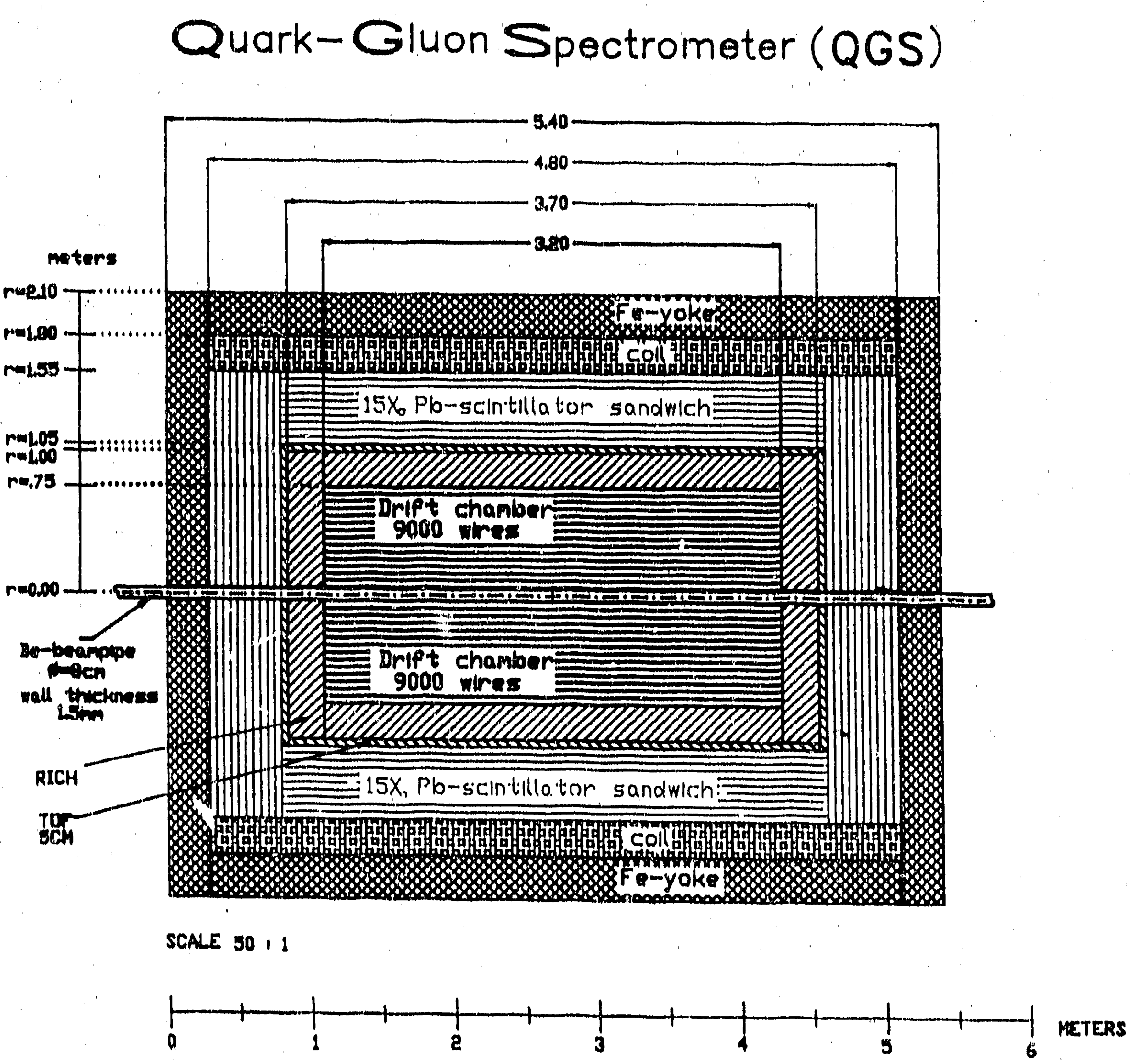

Figure 2: The Central detector: Quark-Gluon Spectrometer (QGS)

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